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PERFORMANCE REPORT

NEURAL NETWORKS FOR REAL-TIME SENSORY DATA PROCESSING AND SENSORIMOTOR CONTROL

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1. Experimental Work

In our experimental work we have completed several studies and have begun at least one more long term project. These include observations in both motion analysis and electrophysiological techniques.

Perhaps the most significant accomplishment of this period is the completion of motion analysis measurements on the basic movements that make up the escape turns. This work has now been accepted for publication in a paper (Nye and Ritzmann, 1992) that will serve as a very useful baseline for all future experimentation on the escape system. In this paper we report that the escape system utilizes at least three different types of turning movements, depending upon the front-back location of the wind source. The paper also documents observations that suggest that several of the joint movements incorporate proprioceptive information into their movements.

Beyond this basic study, we also completed the study on leg lesion. Unfortunately, this study resulted in ambiguous findings. Although animals tend to regain some facility in turning when observed under free ranging conditions, we were not able to reproduce these findings with any confidence in the tethered preparation. It would, therefore, be difficult to make any definitive statements about the changes in leg movement that were made in the free ranging situation. As a result, we have decided to discontinue this project for the time being.

An additional observation was made in the leg lesion study that will be very useful as the project begins to move toward including walking movements. The change from tripod to quadruped gait that was observed when mesothoracic legs were removed was dramatic and immediate. These changes can be easily documented with the tethered preparation.

In physiological studies, Songhai Chai completed a study that documented the relative latency of giant interneurons (GIs) in response to wind from various different directions. The results were in some ways surprising. Earlier reports based on indirect comparisons of large populations of GIs left some authors to conclude that there are large latency differences between the large ventral giant interneurons (vGIs) and the smaller dorsal giant interneurons (dGIs) and smaller vGIs (Westin et. al., 1976). Indeed, this has always been somewhat puzzling, since the latency differences were longer than would be expected if the only difference was the slower conduction velocity found in the smaller dGI axons. As a result, some authors suggested that the cercal afferents may not make direct connections with the dGIs. Nevertheless, morphological observations suggests that these connections are indeed monosynaptic.

Using direct observations of intracellularly recorded pairs of GIs, Chai may now have laid this controversy to rest. Latency changes with wind direction. In the preferred directions of

dGIs there is no large latency difference between dGIs and vGIs. Indeed, in some cases dGI action potentials arrive prior to those of the vGI. A similar observation is made in comparing the large vGI (numbers 1-3) latencies with those of the smaller vGI 4. In trials that recorded GI4 with other vGIs, the responses occurred at essentially the same time. This has important implications when considering the summation of vGI activity at the level of thoracic interneurons. It means that all of the vGI activity will, in fact, be summed, not just the large vGIs as some investigators have assumed.

Again, when the responses of directional vGIs such as GIs 1 and 3 are observed, there is a large increase in latency as the wind direction moves away from the preferred directions. This change in latency should enhance the directional characteristics of the vGI population. For example, in response to a wind from the left side, left GI 1 will not only evoke more action potentials than right GI 1, but those action potentials will arrive in the thoracic ganglia several milliseconds sooner than those in the right GI1.

With these data, we are now moving on to an analysis of the wind fields of the cells that are postsynaptic to the vGIs. We refer to these as type A thoracic interneurons (TI_As). We hope to generate detailed reproducible wind fields for many of the TI_As. If this can be accomplished, we will be in an excellent position to model the transfer function between two identified populations of interneurons (vGIs and TI_As). We can then ask questions regarding the presynaptic inputs that result in these wind fields. The results will go a long way to understanding how this circuit forms appropriate orientation decisions. This information will ultimately be useful in developing context dependent orientation control circuits for future robot development.

2. Modeling and Simulation

We have continued to extend the capabilities of our software simulator. Hidden line removal and color shading have been added to the graphical display. The simulator can now display 3 dimensional animations of the output of a dynamic simulator for legged systems developed by Roger Quinn and a graduate student. The simulator and and dynamic model run as two separate processes and communicate via UNIX sockets. Eventually, two-way communication between the simulator and the dynamic model will be possible, so that the user can interactively manipulate the model through the graphical interface of the simulation system. We are also planning to generalize the dynamic modeling system so that it can be easily reconfigured. This will also us to easily explore the significance of different dynamics models, or to run dynamic simulations of the cockroach and robot simultaneously. This later capability will be quite important when trying to transfer control strategies from the insect to the robot. A Master's Thesis which fully documents the simulation system should be completed by the end

of the year.

We have also been continuing our development of temporal models of the vGIs. Because complete voltage-clamp data is not currently available for the vGIs, we have been exploring the use of genetic algorithms to fit the parameters of integrate-and-fire neural models to given spike train data. We first applied this technique to selected neurons in the *Tritonia* swim central pattern generator. Since Getting has already developed integrate-and-fire models for these neurons, this allowed us to test our approach and to fine-tune various parameters required by the genetic algorithm. We subsequently applied our approach to the vGIs and have developed several integrate-and-fire models which reproduce the essential firing frequency relationships of the spike train data. A Master's Thesis describing this work will be completed before the end of the summer.

Finally, we have continued our work on using genetic algorithms to evolve continuous-time recurrent neural networks. In a previous performance report, we described the use of this technique to evolve dynamical neural network controllers for autonomous agent control, specifically chemotaxis and hexapod locomotion. More recently, we have applied this approach to more general control problems, including second order linear plants and a nonlinear aircraft model. Both genetic algorithms and a random walk search technique were used to find settings of the network parameters which optimized some performance functional of the closed-loop system. We found that small (3-4 node) neural network controllers could track novel reference signals. These controllers were also robust to disturbances and variations in plant parameters. Interestingly, though many of the controllers that we produced had similar performance, their internal operation was often completely different. A paper describing some of this work has been submitted to *Neural Computation*. A Master's Thesis describing in depth the aircraft control application will be completed by the end of the summer.

3. Robotics

We have completed our study of the applicability of leg coordination mechanisms that have been described in the stick insect to hexapod robot locomotion control. We found that, like our original locomotion controller, these coordination mechanisms lead to insect-like gaits across a wide range of walking speeds. A series of lesion studies have demonstrated that this approach is also quite robust to removal of individual mechanisms and variations in mechanism strength. A paper describing these experiments has been submitted to *IEEE Journal of Robotics and Automation*.

Construction of a large (approximately 3' by 6') treadmill has recently been completed. This treadmill will allow us to perform long walking experiments while our robot is tethered to its power supply and control computer. The treadmill also allows various obstructions to be at-

tached in order to simulate complicated terrain.

Construction has also begun on several pieces of hardware that will be used in the next generation robot. For example, we have been implementing various leg designs having three degrees of freedom. In addition, new analog position controllers with software-controlled stiffness to simulate the properties of muscle are being implemented.

Publications

Beer, R.D., Chiel, H.J., Quinn, R.D., Espenchied, K. and Larsson, P. (1992). A distributed neural network architecture for hexapod robot locomotion. *Neural Computation* 4(3):356-365.

Chiel, H.J. and Beer, R.D. (1991) Simulation of adaptive behavior. *Current Opinion in Neurobiology* 1(4):605-609.

Beer, R.D. and Gallagher, J.C. (in press). Evolving dynamical neural networks for adaptive behavior. To appear in *Adaptive Behavior.*

Chiel, H.J., Beer, R.D., Quinn, R.D. and Espenschied, K. (in press). Robustness of a distributed neural network controller for a hexapod robot. To appear in *IEEE Transactions on Robotics and Automation.*

Nye, S.W. and Ritzmann, R.E. (in press). Motion analysis of leg joints associated with escape turns of the cockroach, *Periplaneta americana.* To appear in *J. Comp. Physiol. A.*

Beer, R.D., Ritzmann, R.E. and McKenna, T., Eds. (in press). *Biological Neural Networks in Invertebrate Neuroethology and Robotics*. Academic Press.

Beer, R.D. and Chiel, H.J. (in press). Simulations of cockroach locomotion and escape. To appear in R.D. Beer, R.E. Ritzmann and T. McKenna (Eds.), *Biological Neural Networks in Invertebrate Neuroethology and Robotics.* Academic Press.

Ritzmann, R.D. (in press.). The neural organization of cockroach escape and its role in context-dependent orientation. To appear in R.D. Beer, R.E. Ritzmann and T. McKenna (Eds.), *Biological Neural Networks in Invertebrate Neuroethology and Robotics.* Academic Press.

Quinn, R.D. and Espenschied, K.S. (in press). Control of a hexapod robot using a biologically-inspired neural network. To appear in R.D. Beer, R.E. Ritzmann and T. McKenna (Eds.), *Biological Neural Networks in Invertebrate Neuroethology and Robotics*. Academic Press.

Chiel, H.J. and Beer, R.D. (in press). Neural and peripheral dynamics as determinants of patterned motor behavior. To appear in D. Gardner (Ed.), *The Neurobiology of Neural Networks.* MIT Press.

Submitted

Picardo, L., Smith, R. and Beer, R.D. Continuous-time recurrent neural networks for control. Submitted to *Neural Computation*.

Espenschied, K.S., Quinn, R.D., Chiel, H.J. and Beer, R.D. Leg coordination mechanisms in stick insect applied to hexapod robot locomotion. Submitted to *IEEE J. Robotics and Automation*.

Quinn, R.D., Beer, R.D, Chiel, H.J., Espenschied, K and Larsson, P. Biologically-inspired neural control of a mechanical hexapod. Submitted to *ASME J. of Dynamic Systems, Measurement and Control*.

In Preparation

"Reconstruction of Ventral Giant Interneuron Windfields in the Cockroach Using Constrained Backpropagation," by Randall D. Beer, Gary J. Kacmarcik, Songhai Chai, Roy E. Ritzmann, and Hillel J. Chiel.